$K \to \pi\nu\bar{\nu}$ in and beyond the SM

Yuval Grossman

Technion

Rare Kaon decays

Many interesting modes beside $K \to \pi\nu\bar{\nu}$

- LFV modes, $K_L \to \mu e$, $K \to \pi\mu e$, ...
- L violation modes, $K^+ \to \pi^-\ell^+\ell^+$, ...
- Rare FCNC, $K_L \to \pi^0\ell^+\ell^-$, ...

Yet, I will talk about $K \to \pi\nu\bar{\nu}$.

Some references

- Littenberg, 1989
- Buchalla and Buras, 1990s
- Grossman and Nir, 1997
- Nir and Worah, 1997
- Falk and Petrov, 2001
- D'Ambrosio and Isidori, 2001
- Grossman, Isidori and Murayama, 2003

Outline

- $K \to \pi\nu\bar{\nu}$ in specific models
  - General considerations
  - Standard Model
  - New physics
- General properties of $K_L \to \pi\nu\bar{\nu}$
  - Why is $K_L \to \pi\nu\bar{\nu}$ CP violating?
  - What kind of CP violation?
  - Possible CP conserving contributions
- Conclusions

$K \to \pi\nu\bar{\nu}$ in specific models

Why is $K \to \pi\nu\bar{\nu}$ so clean?

The general problems with hadronic decays are:

- Hadronic matrix elements
- Long distance effects

Why is $K \to \pi\nu\bar{\nu}$ so clean?

The general problems with hadronic decays are:

- Hadronic matrix elements $\Leftarrow$ Isospin
- Long distance effects $\Leftarrow$ Neutrinos

Why is $K \to \pi\nu\bar{\nu}$ so clean?

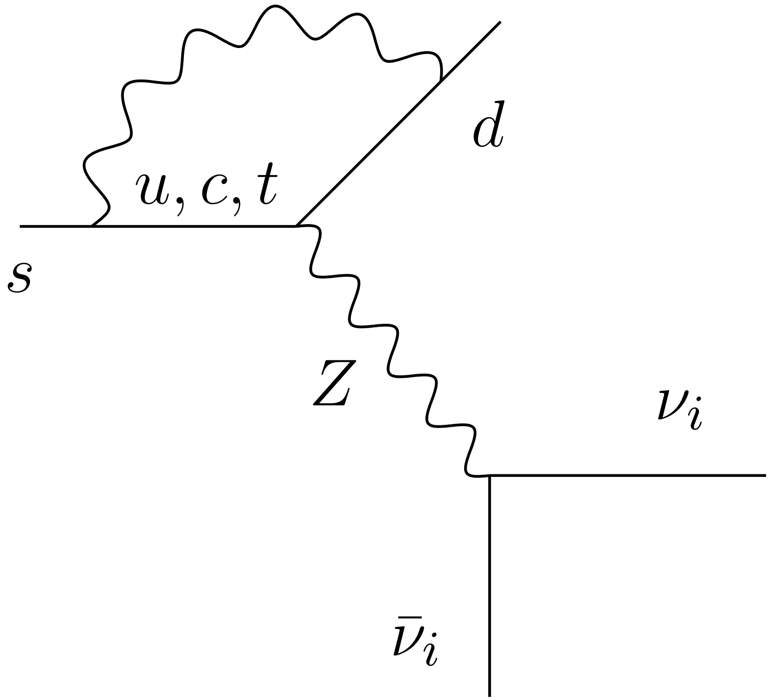
The general problems with hadronic decays are:

- Hadronic matrix elements $\Leftarrow$ Isospin
- Long distance effects $\Leftarrow$ Neutrinos

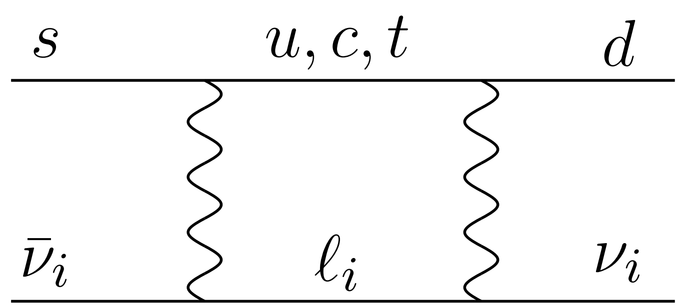
Therefore the $K \to \pi\nu\bar{\nu}$ decays are very interesting

- Exclusive hadronic decays that we can calculate in the SM and its extensions
- The measured rates are sensitive to fundamental parameters

Example: the standard model



Penguin and box diagrams



$$A(K \to \pi\nu\bar{\nu}) = \sum_{q=u,c,t} A_q$$

$K \to \pi\nu\bar{\nu}$ in the SM

$$A(K \to \pi\nu\bar{\nu}) = \sum_{q=u,c,t} A_q$$

where

$$A_q \sim m_q^2 V_{qs}^* V_{qd} \sim \begin{cases} \Lambda_{QCD}^2 \lambda & up \\ m_c^2(\lambda + i\lambda^5) & charm \\ m_t^2(\lambda^5 + i\lambda^5) & top \end{cases}$$

- Hard GIM, negligible LD effects
- $K^+ \to \pi^+\nu\bar{\nu}$: top dominant, charm is important
- $K_L \to \pi\nu\bar{\nu}$: CP violating, almost pure top

$K^+ \to \pi^+ \nu\bar{\nu}$ in the SM

The fundamental Wolfenstein parameters: λ, A, ρ and η

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = C_+ |A|^4 \times \left[\eta^2 + (\rho - \rho_c)^2\right] = O(10^{-10})$$

- C_+ is known
- ρ_c includes the charm effect, with small theoretical errors
- The largest error in extracting ρ and η is from A

$K_L \to \pi\nu\bar{\nu}$ in the SM

$$\mathcal{B}(K_L \to \pi\nu\bar{\nu}) = C_L |A|^4 \times \eta^2 = O(10^{-11})$$

- CP violating decay
- Very small theoretical error in C_L
- The largest error in extracting ρ and η is from A
- In the ratio A cancels

$$\frac{\mathcal{B}(K_L \to \pi\nu\bar{\nu})}{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})} = \frac{C_L}{C_+} \times \frac{\eta^2}{\eta^2 + (\rho - \rho_c)^2}$$

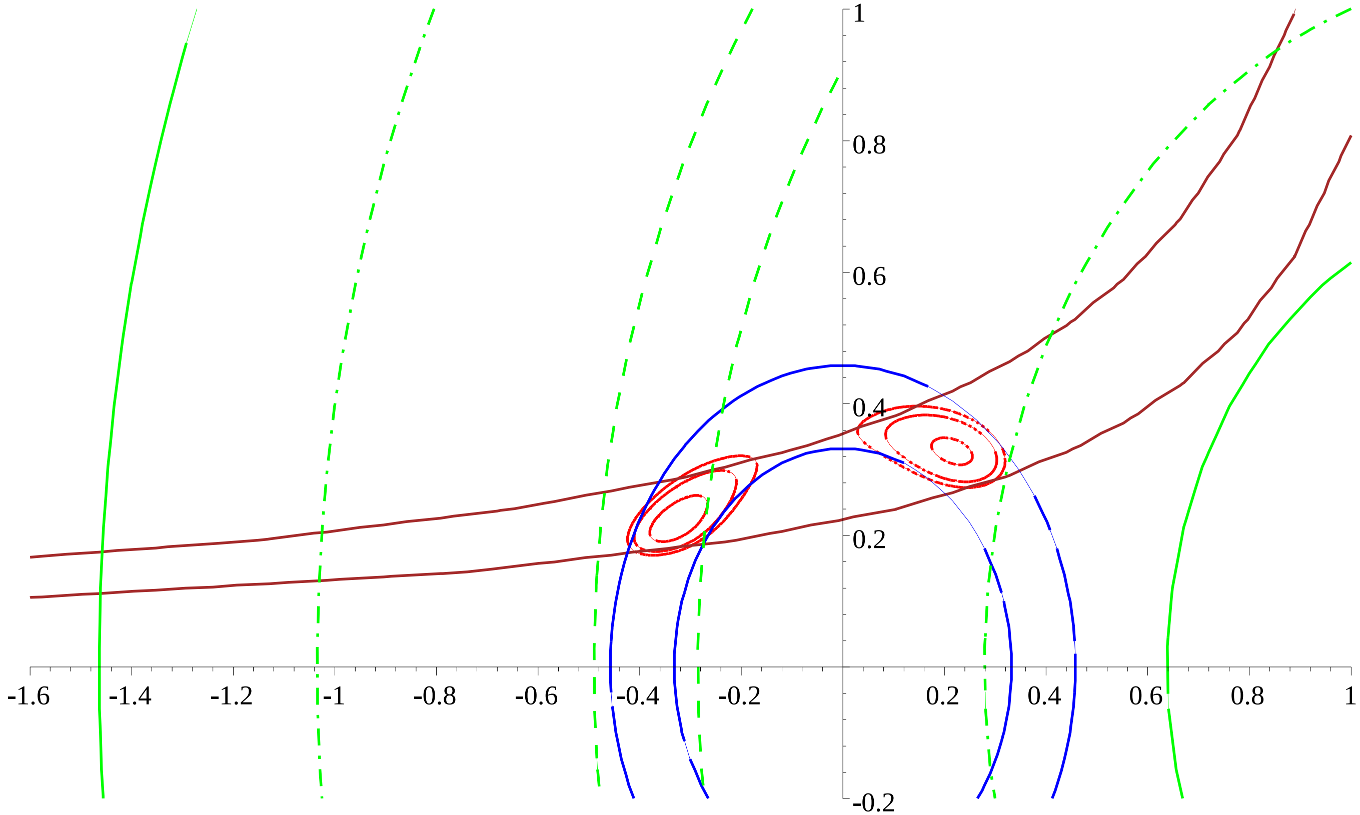
New physics effects

New physics can affect the rates in many ways

- Significant new physics only in the B sector
- Minimal flavor violation: flavor violation is confined to the SM Yukawa couplings
- Significant new physics in $K \to \pi\nu\bar{\nu}$ decays

New physics only in the B sector

G. Isidori

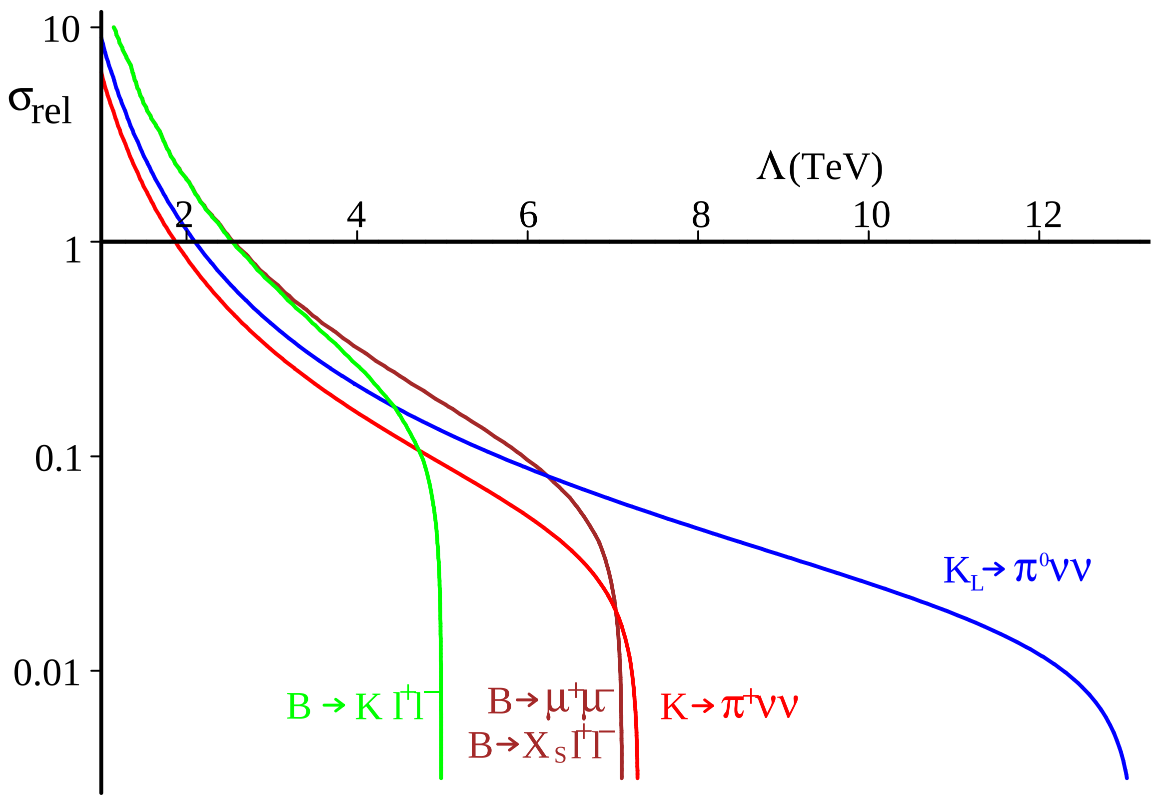


- The green lines: central value, 1σ and 90% CL

Minimal flavor violation

- One effective new parameter: the new physics scale
- Small effects, but $K \to \pi\nu\bar{\nu}$ have very high sensitivity

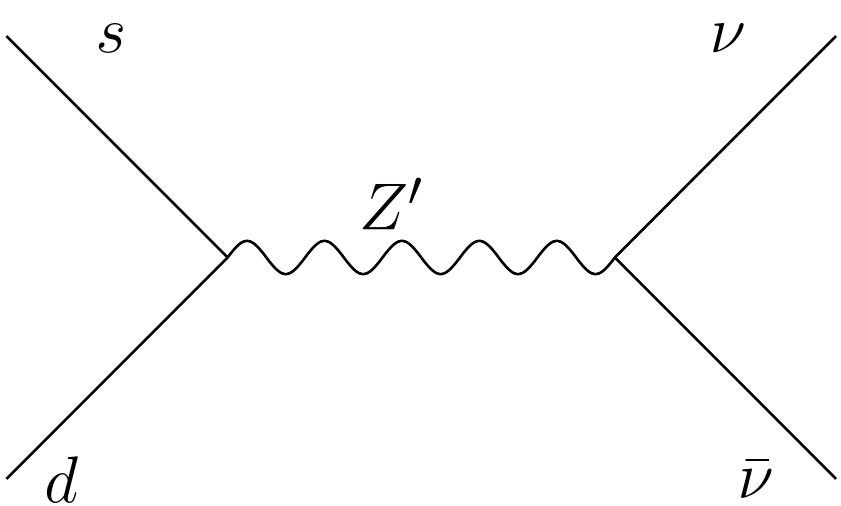
D'Ambrosio, et al.



Non minimal new physics effects

Generic new physics can have large effect with

1. Low scale new physics
2. New flavor violation



$$\propto \quad \frac{\kappa_{sd}^{*}\kappa_{\nu\nu}}{m_{Z'}^{2}}$$

Generically, new physics affects B and K differently

General properties of $K_L \to \pi\nu\bar{\nu}$

Why is $K_L \to \pi\nu\bar{\nu}$ CP violating decay?

- In general, three body decays do not have definite CP
- $\pi^+\pi^-$ is CP even
- $\pi^+\pi^-\pi^0$ can have both CP even and CP odd components

Is $K_L \to \pi\nu\bar{\nu}$ a true CP violating decay?

CP violation in $K_L \to \pi\nu\bar{\nu}$

We neglect ε_K and

1. Consider only left handed neutrinos
2. Assume lepton flavor conservation
3. Neglect small m_K/m_W effects

The only dimension 6 operator that mediate $K_L \to \pi\nu\bar{\nu}$ is

$$O_{sd}^{ii} = \bar{s}\gamma_\mu d \times \bar{\nu}_L^i \gamma^\mu \nu_L^i$$

- This operator produces $\pi^0\nu_i\bar{\nu}_i$ in a CP even state
- We can think of it as $K_L \to \pi Z^*$ two body decay
- Since K_L is CP-odd, $K_L \to \pi\nu\bar{\nu}$ is CP violating

CP properties of the operators

- We choose
$$|K_L\rangle = |K\rangle + |\bar{K}\rangle$$
- The hadronic matrix element that enter $K_L \to \pi\nu\bar{\nu}$ transform under CP as
$$\langle\pi|\bar{s}\Gamma d + \bar{d}\Gamma s|K_L\rangle \xrightarrow{CP} \langle\pi|\eta_{CP}(\Gamma)(\bar{s}\Gamma d + \bar{d}\Gamma s)|K_L\rangle$$
- Since we consider only vector interaction where $\eta_{CP}(V) = -1$, $K_L \to \pi\nu\bar{\nu}$ requires CP violation

What is the kind of CP violation?

In B physics we talk about three types of CPV

1. "Direct" $|\bar{A}/A| \neq 1$
2. "Indirect" $|q/p| \neq 1$
3. Interference between mixing and decay

$$\arg\left(\frac{q\bar{A}}{pA}\right) \neq 0$$

- δ_L is of the second type, "Indirect"
- $\mathcal{R}e(\epsilon)$ is "Indirect" and $\mathcal{I}m(\epsilon)$ is the third type
- $\mathcal{R}e(\epsilon')$ is "direct" and $\mathcal{I}m(\epsilon')$ is the third type
- $K_L \to \pi\nu\bar{\nu}$ is of the third type $\Rightarrow$ the clean type

The third type of CPV

$$\lambda \equiv \frac{A(\bar{K} \to \pi\nu\bar{\nu})}{A(K \to \pi\nu\bar{\nu})} \frac{q}{p}$$

Then we get

$$\frac{\Gamma(K_L \to \pi\nu\bar{\nu})}{\Gamma(K_S \to \pi\nu\bar{\nu})} = \frac{1+\lambda^2 - 2\mathcal{R}e\lambda}{1+\lambda^2 + 2\mathcal{R}e\lambda} \quad \xrightarrow{|\lambda|=1} \quad \tan^2\theta$$

where

$$\theta \equiv \arg(\lambda)$$

In the SM $\theta \approx \beta$, up to calculable charm contribution

Bounding the $K_L \to \pi\nu\bar{\nu}$ rate

$\Gamma(K_S \to \pi\nu\bar{\nu})$ may never be measured. We thus use isospin

$$\sqrt{2}A(K^0 \to \pi^0\nu\bar{\nu}) = A(K^+ \to \pi^+\nu\bar{\nu})$$

Then we get

$$R \equiv r_{is}\frac{\Gamma(K_L \to \pi\nu\bar{\nu})}{\Gamma(K^+ \to \pi^+\nu\bar{\nu})} = \sin^2\theta$$

with $r_{is} = 0.954$ takes care of isospin breaking

- R measured θ cleanly assuming only isospin
- Using $\sin^2\theta \leq 1$ we get a model independent bound

More general $K_L \to \pi\nu\bar{\nu}$

We can have CP conserving contribution once we relax each of the above mentioned assumptions

1. Consider also right handed neutrinos
2. Allow for lepton flavor violation
3. Include small m_K/m_W effects

Right handed neutrinos

Consider right-handed neutrinos. Then there are new dimension 6 scalar and tensor operators. For example

$$(\bar{s}\,\Gamma_S d) \times \bar{\nu}_R \Gamma_S \nu_L$$

- Γ_S is a scalar operator
- Under CP
$$\Gamma_S \xrightarrow{CP} \Gamma_S \qquad \Gamma_V \xrightarrow{CP} -\Gamma_V$$
- Scalar operators generate $K_L \to \pi\nu\bar{\nu}$ in the CP limit, with one LH and one RH neutrino (SM: both are LH)
- The effect due to neutrino masses is tiny
- The spectrum is different from the standard spectrum

m_K/m_W effects

Under CP

$$\nu(k_1)\bar{\nu}(k_2) \xrightarrow{CP} \nu(k_2)\bar{\nu}(k_1)$$

- For a CP eigenstate the ν and $\bar{\nu}$ must have the same spectrum
- The standard dimension 6 operator generates a symmetric spectrum
- Dimension 8 operators do not necessarily generate a symmetric spectrum
- A general spectrum is a sum of a symmetric and an antisymmetric spectrum. That is, CP-even and CP-odd
- In the SM this operator comes from the box diagram as long as we keep the external momenta

Lepton number violation

Consider a CP conserving new physics model where

$$A(K \to \pi \nu_i \bar{\nu}_j) \neq 0 \qquad A(K \to \pi \nu_j \bar{\nu}_i) = 0$$

Due to CP

$$A(\bar{K} \to \pi \nu_i \bar{\nu}_j) = 0 \qquad A(\bar{K} \to \pi \nu_j \bar{\nu}_i) \neq 0$$

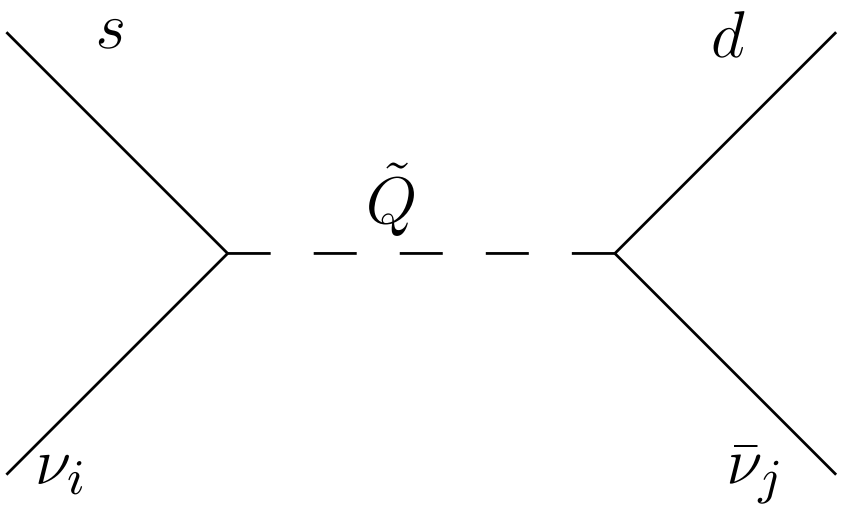
Then

$$\sqrt{2}\, A(K_L \to \pi \nu_i \bar{\nu}_j) = A(K \to \pi \nu_i \bar{\nu}_j) + A(\bar{K} \to \pi \nu_i \bar{\nu}_j) \neq 0$$

- In the standard CP conserving case, $A(K_L \to \pi \nu \bar{\nu}) = 0$ since K and $\bar{K}$ cancel each other
- This cancelation does not occur once these decay amplitudes have different magnitudes

Example: SUSY without R-parity

We get an effective leptoquark interaction: $\lambda_{ik}\bar{L}_i Q_k S$



$\propto \lambda_{is}\lambda_{jd}$

- Then

$$A(K_L \to \pi\nu_i\bar{\nu}_j) \propto (\lambda_{is}\lambda_{jd} - \lambda_{id}\lambda_{js})$$

which, in general, is finite in the CP limit

Lepton number violation: mass matrices

We know that lepton number is violated by neutrino mass

Q: Can it generate CP conserving contribution to $K_L \to \pi\nu\bar{\nu}$?

A: Practicality no. We can rotate to interaction basis

Can the CP violating contribution be sensitive to the mixing matrix?

- Neutrino mixing: The effects are proportional to m_ν
- Sneutrino mixing: The $K_L \to \pi\nu\bar{\nu}$ rate depends on the sneutrino masses but not their mixing angles
- Sneutrino and Slepton mixing. The rate depends on the product of the two rotation matrices

Conclusions

Conclusions

- The $K \to \pi\nu\bar{\nu}$ decays are very clean and interesting
- It would be nice to know their rates
- Even in the era when flavor physics is dominated by B's, kaons are important